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AN INERTIAL HEAD-ORIENTATION TRACKER WITH AUTOMATIC DRIFT COMPENSATION FOR USE WITH HMD'S

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ABSTRACT

Current head-tracking technologies suffer from limitations such as delay, limited range, vulnerability to interference, line-of-sight requirements and high cost. In principle, the methods of Inertial Navigation Systems (INS), applied to head-tracking, could overcome these problems. However, inertial head-tracking has been largely neglected due to the difficulty of making a small, light INS that does not drift too much. In order to evaluate the suitability of inertial sensors for use in virtual environment and teleoperator head-tracking applications, an inertial head-orientation tracker has been built and bench-tested for accuracy, resolution, noise, and latency. Yaw, pitch and roll of the head are computed by Euler integration of the outputs of three orthogonal angular rate sensors. Drift compensation is accomplished by making use of natural pauses in head motion to obtain stable readings from a two-axis fluid inclinometer and a fluxgate compass. The system achieves 0.1 ms lag, 0.008° angular resolution, and an unrestricted working volume. The pitch and roll axes, using a fluid inclinometer for drift compensation, achieve 1° angular accuracy. The drift compensation of the yaw axis using a compass has not yet been evaluated. The results indicate excellent potential for the use of inertial technology in head-tracking, and work is under way to extend the system to 6 degrees of freedom.

1. Introduction

The problem of making a fast, accurate, and economical head-tracker which operates throughout a large workspace is crucial to virtual reality and other Head-Mounted Display (HMD) applications. Extensive research has been devoted to the development of optical, magnetic, acoustic and mechanical tracking systems, but head-trackers are still one of the weakest links in existing virtual-environment systems. The fastest and potentially most accurate trackers are mechanical, but these are by nature clumsy and range-restrictive. The largest tracking range has been achieved at UNC by optoelectronic methods [Ward *et al.*, 1992], but this type of system is extremely expensive and difficult to install, calibrate, and maintain. Ultrasonic trackers are inexpensive, but must sacrifice speed to achieve reasonable

range and are sensitive to acoustical interference, reflections, and obstructions. The magnetic trackers are the most popular because of their convenience of operation (they don't even require line of sight), but the maximum range is a few feet and distortions caused by metallic objects can be problematic. For reviews of the existing four head-tracker technologies, see [Meyer *et al.*, 1992; Ferrin, 1991; Bhatnagar, 1993]. This paper will consider only the head-tracking problem, but it should be understood that the results may also be applied toward tracking other body parts with appropriate modifications.

This paper introduces a fifth candidate head-tracking technology which potentially offers very large range, insignificant delay, immunity to interference, and no line-of-sight requirements. Accelerometers and rate gyroscopes have been used for decades in Inertial Navigation Systems (INS) for ships, planes, missiles and spacecraft. The recent development of micromachined accelerometers and angular rate sensors makes the application of INS technology to head-tracking conceivable.

The basic type of INS which is applicable to head-tracking is called Strapdown INS, and consists of three orthogonal accelerometers and three orthogonal rate gyros fixed to the object being tracked. The orientation of the object is computed by jointly integrating the outputs of the rate gyros (or micromachined angular rate sensors), whose outputs are proportional to angular velocity about each axis. Changes in position can then be computed by double integrating the outputs of the accelerometers using their known orientations. If the actual acceleration is $\vec{a}$ and the acceleration of gravity is $\vec{g}$, then the acceleration measured by the triaxial accelerometers will be $\vec{a}_{measured} = \vec{a} + \vec{g}$. To obtain the position it is necessary to know the direction and magnitude of $\vec{g}$ relative to the tracked object at all times in order to double integrate $\vec{a} = \vec{a}_{measured} - \vec{g}$. Detailed information about INS is available in many books on the subject, such as [Broxmeyer, 1964; Parvin, 1962; Britting, 1971].

There are many compelling advantages of using inertial head-tracking instead of one of the other four technologies. Since inertial measurements are not relative to any fixed equipment in the room, it is theoretically possible to track the head with undiminished performance over an unlimited range or working volume. For many applications, such as architectural walkthroughs, see-through HMDs, entertainment, and psychophysical experiments on sensorimotor integration, this is a very important feature. A second major advantage of inertial head-tracking is that it can be very fast. The integrated outputs of angular rate sensors and accelerometers are ready to be used without any delay-ridden filtering. The only other head-trackers which have essentially instantaneous response are mechanical trackers, which suffer from very strict range limitations. Speed, or responsiveness, is known to be a very important aspect of tracker performance. Excessive delay added into the head-motion-to-visual-feedback loop destroys the illusion of presence and can cause simulator sickness [Oman, 1991]. A third advantage of INS techniques for head-tracking is that they are free of the interference and line-of-sight problems that plague all the other trackers. A pure inertial system does not send or receive any signals from its environment and therefore its performance will not be affected

by any kind of EMI or occlusions of acoustic or optical sources, or the operation of any other tracking systems in its vicinity. The only external field that a pure INS senses is gravity, and the movement of mass in the vicinity of the tracker produces gravitational variations so tiny that they will have no effect on the accuracy of the tracker. One final advantage is the ability to sense orientation directly. Acoustic and outside-in optical trackers only directly measure position. Orientation is then computed from the positions of three fixed points on the head. Therefore, the angular resolution is limited by the uncertainty in the position measurements as well as the distance between the three fixed points on the head. With 100 mm spacing between the fixed points, a positional jitter of ± 1.0 mm causes an orientational jitter of up to $\pm 1.1°$. Inertial systems, by measuring the angular degrees of freedom directly, make possible a self-contained orientation-tracking module whose performance is in no way affected by the quality of the position-measuring subsystem, or even the lack thereof. The existence of such independent orientation and position subsystems would make possible a more modular approach to VE system design. The designer would be able to select an orientation-tracker and a position-tracker with appropriate specifications for the application. In an extreme case, such as a VE in which the user navigates by making hand gestures and not by walking about, it may be perfectly workable to use no position-tracker at all.

Until recently, the foremost problem with using an INS system to track a human head was probably weight. A traditional navigation gyroscope is at least the size of a soda can and much heavier. Furthermore, they are extremely expensive. In the past few years some new devices have come to the market which are already of reasonable weight and price for use in head-tracking, and the size and cost will continue to come down rapidly.

A second difficulty with using gyroscopes for head-orientation tracking is drift, which makes the virtual world appear to gradually rotate about the user's head even when the user is not moving. By measuring the output of an angular rate sensor while it is at rest, it is possible to know its output bias and subtract the bias off of all subsequent measurements. However, there is inevitably some random noise produced by the sensor in addition to it's bias. Passing a zero-mean unit white noise $f(t)$ through an integrator produces a Brownian Motion Process $x(t)$ with a mean of zero and standard deviation $\sigma_x = \sqrt{t}$ [Papoulis, 1991]. Thus, in the short term, the angular drift is a random walk with RMS value growing proportional to $\sqrt{t}$. However, the small bias that remains even in a well-calibrated system leads to a drift error that grows as t, which will eventually exceed the Brownian Motion error that grows as $\sqrt{t}$.

Difficulties with calculating position from the output of accelerometers are much more severe. Whereas the bias in the output of an angular rate sensor, when integrated, leads to an orientation error that grows linearly with time, the output bias of an accelerometer, when double integrated, leads to a position error that grows quadratically with time. In a system with excellent bias nulling, the short-term positional drift will be a random variable $y(t)$ with mean of zero and standard deviation $\sigma_y = t^{3/2}/\sqrt{3}$ [Foxlin, 1993]. Once again, the RMS error due to noise

grows a factor of $\sqrt{t}$ more slowly than the deterministic drift. However, in this case they both grow faster than t, which makes the problem of obtaining position from accelerometers much more sensitive than the problem of obtaining orientation from gyroscopes.

If the amount of drift is intolerable, it may be curtailed by periodically resetting the system with values obtained from other sensors. For the rotational degrees of freedom, it is possible to correct drift without reference to any equipment in the room, and therefore without loss of the advantages of being self-contained. Orientation of a static body can be measured with a pendulum and a compass. The human head is often quite still for periods of several seconds, which is long enough to obtain stable readings from a pendulum and compass and use them to reset the drift.

For position-tracking there is no obvious way to aid the accelerometers with any other self-contained sensor. The best choice for an aiding system appears to be a simplified ultrasonic position-tracker. Fortunately, the ultrasonic system used for aiding may produce reliable position fixes far less frequently than it would if used alone, so it can be heavily filtered to remove noise caused by other acoustic sources and even momentary obstructions of the line of sight. Furthermore, it can operate over a room-sized range since fast measurement is not required.

Since inertial tracking is more likely to be successful for orientation than for position, the logical first step is to build and evaluate an inertial orientation sensor. The following sections describe the design, implementation, and evaluation of such a device.

2. Design

Figure 1 is a block diagram outlining the basics of the design. The box labeled "fast angular rate sensors" represents three orthogonally-mounted Systron-Donner GyroChips. Each GyroChip produces a DC voltage output linearly proportional to angular velocity in the range ±1000°/s. The box labeled "slow angular position sensors" represents a Fredericks 0717 two-axis electrolytic fluid inclinometer and an Etak 0220 fluxgate compass. The inclinometer consists of a glass bubble, 1/4" in diameter, with 5 electrodes to sense resistance changes when the bubble is tilted in either the front-back or right-left direction. The fluxgate compass measures magnetic field strength in two orthogonal horizontal directions. Theoretically, these two field components combined with the known tilt should be enough information to compute heading direction (yaw). However, the almost vertical magnetic field in our laboratory has not yet been characterized, and the measurements in this paper are made without yet having fully reduced the yaw drift correction mechanism to practice.

The integration by Euler angles is performed using the equations:

$$\dot{\psi} = P + Q\sin\psi\tan\theta + R\cos\psi\tan\theta \qquad (1)$$

$$\dot{\theta} = Q\cos\psi - R\sin\psi \qquad (2)$$

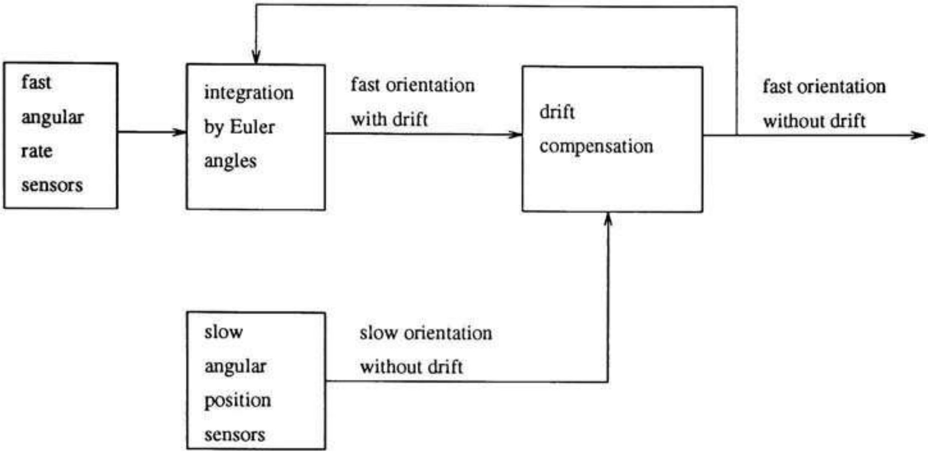

Figure 1: Proposed design of inertial orientation tracker with drift compensation.

$$\dot{\phi} = Q \sin\psi \sec\theta + R \cos\psi \sec\theta. \tag{3}$$

Here P, Q, and R represent the angular velocities of an object around its x, y, and z body-coordinates respectively. According to the coordinate convention in aeronautics, the x-axis points forward, y points right, and z points down. P, Q, and R can be thought of as the outputs of three orthogonal angular rate sensors mounted on the object. ϕ, θ, and ψ, respectively, represent yaw, pitch, and roll, which are defined as the amount of counter-clockwise rotation applied about the z, y, and x body-axes in that sequence to get to its current orientation. Note that Cooke *et al* [1993] use the reverse definitions of ϕ and ψ. Eq. (1–3) aren't actually integral equations at all, but they provide the rates of change of the Euler angles, which can then be integrated to obtain the updated Euler angles. The simplest procedure for integration in a computer is, after each time step Δt, to set

$$\psi(t+\Delta t) = \psi(t) + \dot{\psi}(t)\,\Delta t \tag{4}$$
$$\theta(t+\Delta t) = \theta(t) + \dot{\theta}(t)\,\Delta t \tag{5}$$
$$\phi(t+\Delta t) = \phi(t) + \dot{\phi}(t)\,\Delta t. \tag{6}$$

Note that the increments applied at time t depend on the values of the Euler angles at time t. If those were taken simply as the values computed as the result of the previous integration step, then the accumulation of a little bit of drift would cause the next increment used to be wrong, and the drift rate would accelerate exponentially. To prevent this disaster, the Euler angles used in Eq. (1–3) are taken from the output of the drift compensation step, as shown in the block diagram.

The drift correction scheme used is very simple. Whenever the user's head pauses (which normally happens at least once every 10 seconds) the fluid-filled inclinometer

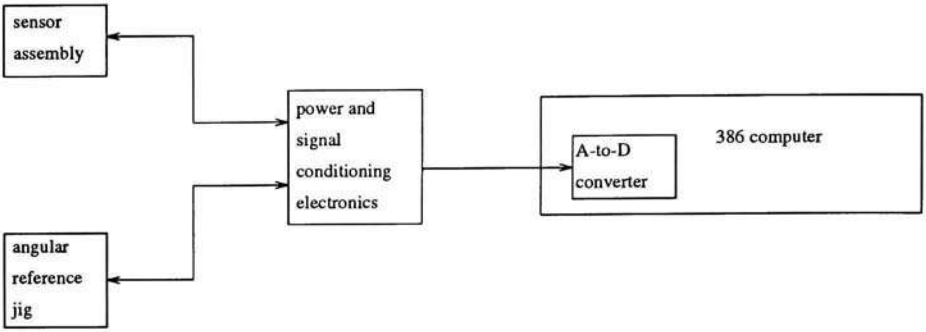

Figure 2: Overview of the apparatus.

will settle to its correct pitch and roll values in about 1/4 second. At this moment, the absolute head orientation is known with high accuracy, and the output variables can be reset to these values, thus annihilating all the drift that has accumulated since the last reset. To prevent sudden orientation shifts from jarring the user, the drift is removed from the output gradually, not all at once.

3. Implementation

The apparatus that was built is shown schematically in Figure 2. The sensor assembly consists of all the sensors bolted to a piece of aluminum L-bracket, with care taken to ensure the orthogonality of the three GyroChips. The assembly measures 2" X $2\frac{1}{4}$" X $3\frac{1}{4}$" and weighs 1 pound. The sensors are cabled to an electronics board which provides appropriate power supplies for all the sensors, and converts all their outputs into buffered DC voltages in the range ±2.5 volts. These signals are read by a Data Translation DT2814 data acquisition board installed in a 386-based personal computer.

In order to calibrate the system, a jig was needed to position the sensor assembly at precisely known angles while reading the outputs. This same jig is also used for the evaluation of the system in the following sections. The jig built consists of a 6" diameter motor bolted to a large heavy aluminum plate with rubber feet. The spindle of the motor is outfitted on one end with a precision potentiometer and on the other end with a bracket assembly which can mount the sensor block in a variety of orientations. Hard rubber stops limited the range of motion to ±90°.

The software implements the processing scheme of Figure 1. System timer interrupts trigger data acquisition from the sensors at precisely controlled periodic time intervals. The processing done by the main loop when new data has been queued is done by two functions, "update_stilltime" and "update_eulers." The first function, "update_stilltime," determines when the outputs of the tilt sensor bubble are reliable, and uses them to update the error variables that will be used in "update_eulers" to compensate drift. The values read from the bubble sensor are

taken as reliable when they have been nearly constant for 1/4 second. Waiting 1/4 second longer after the outputs stop changing not only assures that the readings used are very stable, but also allows averaging of many readings to obtain much better precision than a single reading with 12-bit conversion would accomplish. If on a particular iteration the still time reaches 1/4 second, the averages accumulated over the past 1/4 second are converted into actual pitch and roll angles using look-up tables to compensate for the sensor nonlinearities. The second function, "update_eulers," uses Eq. (1–3) to compute the integration step, then adds the step to the Euler angle output variables while subtracting off a fraction of the error. This function requires 4 trigonometric functions and 19 double-precision floating-point multiplications, and is the rate limiting step in the loop.

After the Euler angle output variables have been updated, they are copied to mirror variables so that they can be accessed by other functions without causing conflict. During normal operation these exported Euler angles are displayed graphically as meter needles on the screen. When the user opts to perform a test run, the angles are also recorded in a data array (which can be saved to a disk file for subsequent analysis) together with corresponding angles of the reference jig.

4. Evaluation

4.1. Drift

Because the tracker incorporates automatic drift compensation, there should be no drift. However, it is of interest to know the uncompensated drift rate in order to calculate how often updates are needed to keep within the desired accuracy tolerance. Furthermore, the yaw drift compensation has not yet been fully implemented, so a measurement of the yaw drift is necessary to characterize the current system.

The drift measurement procedure records the Euler angles once per second for an hour, with the drift compensation mechanism turned off. This protocol is used to permit direct comparison with GyroChip integration test results provided by Systron-Donner [Garcia, 1992]. During the hour of recording, the sensor assembly sits still on a table, so any changes in the output angles are the result of drift. The earth's rotation rate of 15°/hour should not appear in the recordings because the bias measurement routine reads the outputs of the rate sensors, including a steady angular velocity resulting from earth rotation, and treats it as part of the bias.

On several trials, the peak-to-peak deviations over the course of an hour for pitch roll and yaw all fell within the range of 90–300°. These results are quite poor compared to those obtained by Systron-Donner, with peak-to-peak deviations of 1.4–8.3° in an hour. Their tests, however, are performed using an analog integrator circuit based on a precision op-amp. When tested with its input grounded, the op-amp only drifts 0.2° in an hour. By contrast, the head-tracker integrates the sensor digitally after 12-bit A/D conversion, using a fairly complicated nonlinear algorithm. When tested with the inputs of the A/D converters all grounded, the head-tracker drift was still of the same magnitude. This indicates that the A/D conversion or inaccuracy of the bias measurement routine, rather than the sensor

noise, is the dominant cause of drift.

4.2. Accuracy

As previously stated, the yaw drifts and inherently has no accuracy. Accuracy is therefore measured for the pitch and roll outputs only.

The method employed for accuracy measurement was to affix the tracker to the angular reference jig with either the pitch or roll axis aligned with the axis of rotation, and then record the outputs of the tracker and the angular reference jig for one minute with a sampling rate of 48.55 Hz. During the minute, the tracker was rotated randomly by hand in an effort to simulate the type of input motions that would be encountered by a head-tracker in actual use. An effort was also made to provide a variety of motions, fast and slow, with and without frequent pauses, to make sure that the accuracy would not be overly affected by variations in the frequency or duration of the pauses.

The results for both pitch and roll are shown in Figure 3. The top graph for each experiment shows a recording of all the motions during the minute. A dashed line shows the angles recorded by the angular reference jig, and a solid line shows the tracker output for the DOF being tested, although for the pitch experiment the two lines almost coincide. The bottom graph for each experiment shows the error, computed by subtracting the dashed line from the solid line. For pitch, the error ranges from $-1°$ to $+0.5°$ (The positive spike at 45 seconds results from slamming the the angular reference jig hard against its rubber limit stop, thus forcing it past $+90°$ The tracker continues to report the correct angle, but the angular reference jig saturates at $90°$ and produces the error.) The results for roll are not as good as pitch, but still quite acceptable. Note that the error is always negative, so by adding a constant offset to the tracker roll output the maximum error could be reduced from $2.5°$ to half that much.

4.3. Resolution and Noise

The top graph in Figure 4 shows a magnified view of the noise sample that was obtained from the stationary tracker for the purpose of evaluating the resolution. This data record comprises 4096 samples of the yaw output taken at a sampling rate of 145.65 Hz with both attitude and heading drift compensation enabled. The mean has been subtracted, but the data is otherwise unprocessed. A power spectral density analysis reveals that most of the noise energy is concentrated below 1 Hz, which explains why the noise trace looks like a meandering river more than the straight fuzzy caterpillar typical of white or pink noise.

It seems unreasonable to include the very slow fluctuations as "noise" because noise is intended to be a measure of the fast fluctuations in the output of the head-tracker that would lead to distracting scene jitter. Since scene rotations slower than $0.05°/s$ are not even perceptible, let alone distracting, an intuitively reasonable definition of noise for this application is the signal that remains after subtracting from the raw noise signal that low-frequency component which varies more slowly than $0.05°/s$. It was found empirically that lowpass filtering the noise with a cutoff fre-

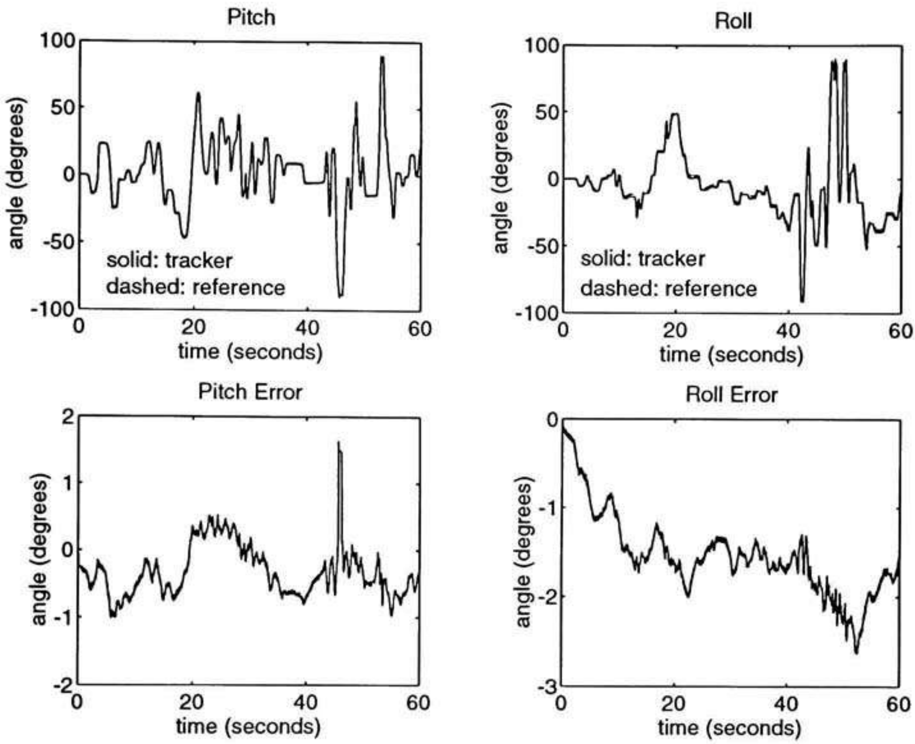

Figure 3: Accuracy during simulated "in-use" head movement.

quency of 0.35 Hz extracts a low-frequency component whose derivative has maxima just under 0.05°/s, which is shown in the middle plot in Figure 4. The bottom plot shows the highpass version of the noise obtained by subtracting the lowpass version from the original. The RMS amplitude of this "de-drifted" noise, 0.0082°, will be taken as the resolution of the head-tracker. This is comparable to the resolution of a mechanical tracker with 16-bit conversion.

4.4. Dynamic Performance

Excessive head-tracker delay has a profoundly destructive effect on VE realism, and can even induce nausea and vomiting. The need for a fast head-tracker is one of the major motivations for this study of inertial head-tracking. It is therefore particularly important to thoroughly evaluate the tracker's dynamic performance. Because the head-tracker is designed to approximate a system $\vec{w}(t) = \vec{v}(t)$, and does a reasonably good job, it is modeled in this section as three separate LTI systems, one for each DOF. Since the three system functions are basically the same,

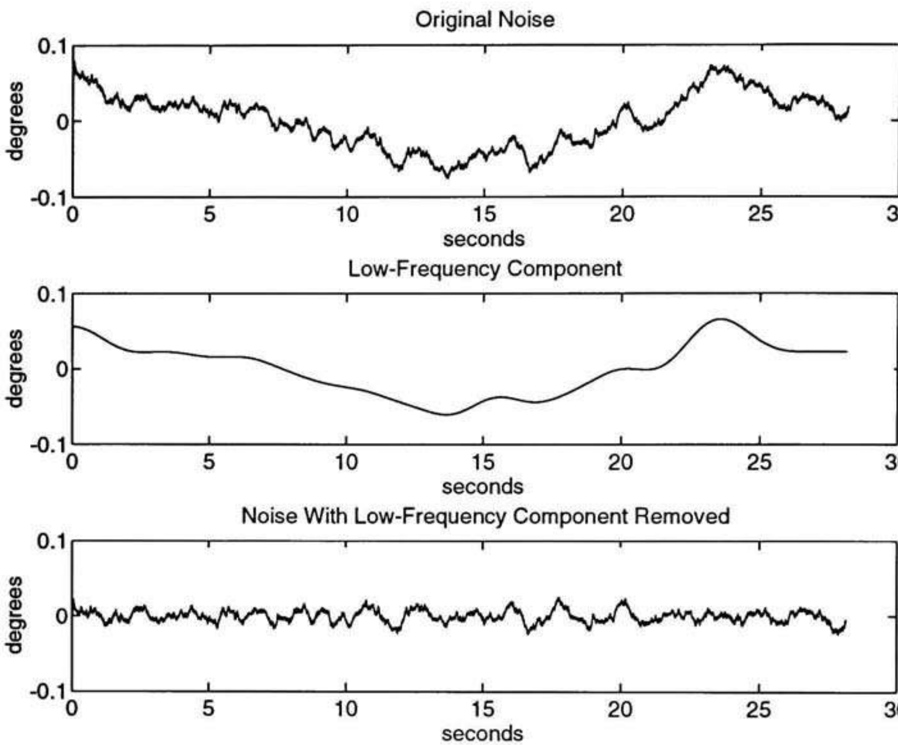

Figure 4: Filtering to obtain a more reasonable noise characterization.

evaluation focuses entirely on determining the system function for pitch.

There are several experimental methods for determining system functions. If the input is electrical, an impulse or white noise signal may be introduced at the input, while recording the output. Fourier transforming the output then yields the system function directly. If the input is mechanical, as for a head-tracker, it is often too difficult to approximate an impulse or white noise. One approach which has actually been used for evaluating other head-trackers [Adelstein *et al.*, 1992] is to record the amplitude and phase response to sinusoids at a handful of different frequencies and plot the results against frequency. Since the testing apparatus and software used in this project makes it easy to simultaneously record the actual pitch angle, $v(t)$, and the pitch output reported by the tracker, $w(t)$, for the same time period $0 \leq t \leq T$, the approach chosen is simply to use $H(f) = \frac{W(f)}{V(f)}$ where $V(f)$ and $W(f)$ are the discrete-time Fourier transforms of $v(t)$ and $w(t)$, computed using a radix-2 FFT algorithm. The benefit of this method is that the excitation signal, $v(t)$, may be anything which contains energy at all the frequencies of interest. This

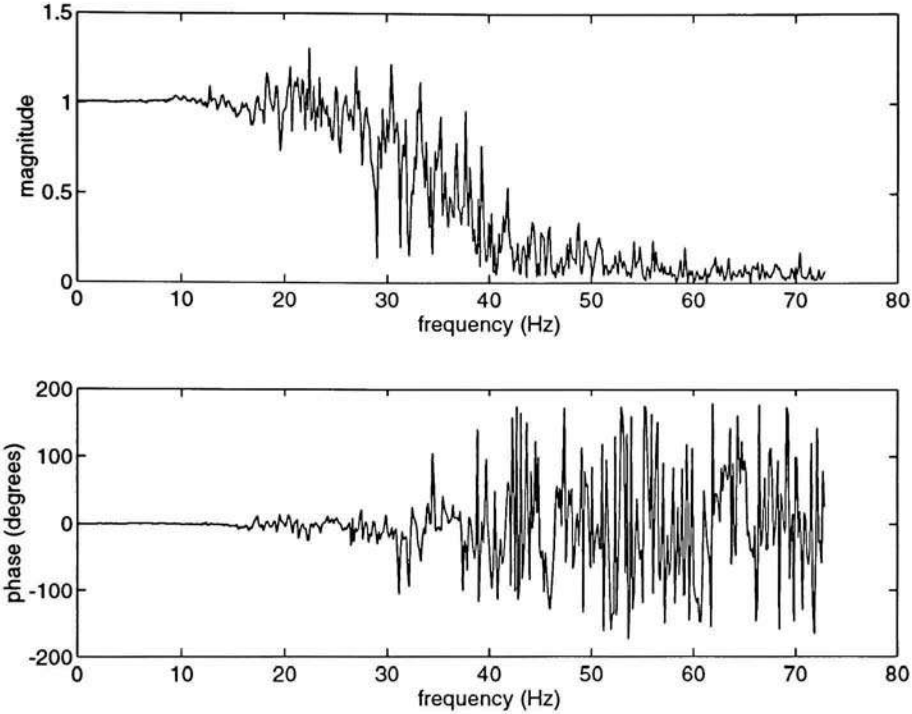

Figure 5: Transfer function magnitude and phase for pitch axis.

makes possible a very simple and low-cost excitation method: the tracker on the reference jig is hand-shaken as vigorously as possible at a variety of frequencies for about 30 seconds, while the excitation angle and tracker output are simultaneously recorded with 145 Hz sampling rate.

Figure 5 shows the system function obtained in the manner described above. Up to about 10 or 15 Hz, the magnitude is 1 and the phase is 0, as desired. At higher frequencies both the magnitude and phase become sporadic. This is because the excitation contains insufficient energy at high frequencies; it does not indicate that the bandwidth of the tracker is only 15 Hz. Given that the bandwidth of the GyroChips is 100 Hz, it is expected that the system function of the tracker would be flat out to the Nyquist frequency of 70 Hz if it could be measured that far. It is not, however, important to demonstrate flat response all the way out to 70 Hz. In a paper specifically on testing dynamic performance of head-trackers, Adelstein [Adelstein *et al.*, 1992], only tested frequency response up to 3.5 Hz, citing the bandwidth of human volitional movement given in [Freund *et al.*, 1984] as 3 Hz. Both the Polhemus Isotrack and Logitech 6-D Mouse showed significant gain rolloff

Specification	Desired	Achieved
Angular Range	yaw: $\pm 180°$ pitch: $+50°, -70°$ roll: $\pm 35°$	yaw: $\pm 180°$ pitch: $\pm 90°$ roll: $\pm 90°$
Positional Range	room size	unlimited
Angular Velocity	$\pm 1000°/s$	$\pm 1000°/s$
Angular Acceleration	$\pm 6000°/s^2$	$> 6000°/s^2$
Angular Accuracy	opaque HMD: yaw: no requirement pitch & roll: 15° max drift rate: 3°/min see-through HMD: 0.009°	pitch & roll: 1° yaw: $\sim 3°$/min drift
Angular Resolution	opaque HMD: 0.03° see-through HMD: 0.009°	0.0082° RMS
Bandwidth	20 Hz	tested to 15 Hz probably flat to 70 Hz
Latency	1 ms	0.1 ms

Table 1: Summary of desired and achieved performance for orientation tracking.

below this frequency. In order to further justify the use of system functions that are only valid to 15 Hz, an additional experiment was performed using the inertial tracker mounted on a headband to record 30 seconds of frenzied head-wagging. Fourier transforming the outputs, it was found that the highest frequencies were produced in the yaw output, and died off almost completely by about 8 Hz.

Having determined from the system function magnitude that the tracker bandwidth is more than adequate for tracking human head motion, it is also possible to obtain an empirical measure of the system lag by looking at the phase response in Figure 5. A least squares linear regression to the phase from 0 to 10 Hz has a slope of 0.037°/Hz which corresponds to a lag of 0.1 ms. The design goals for dynamic performance have clearly been achieved.

5. Conclusions and Directions for Further Work

Table 1 summarizes the evaluation results and compares them to the desired specifications set forth in [Foxlin, 1993]. The results show that the prototype inertial orientation tracker was in most ways successful at meeting the head-tracking needs that have not been met by mechanical, acoustic, magnetic and optical systems.

The range of the inertial tracker is potentially larger than any other head-tracker yet devised. All possible orientations are tracked, although for drift correction to

occur the user must occasionally pause with roll and pitch angles inside the range ±57°. Positional range is also unrestricted. By using long enough wires, the user may wander freely throughout a room of any size. If the application requires the user to travel throughout a large building or outdoors, the wires can be eliminated by telemetry. To be fair, the inertial orientation-tracker achieves unlimited range in position by not tracking position. In extending the inertial head-tracking concept to 6 DOFs, it is likely that translational range will have to be compromised somewhat in order to obtain external position fixes for drift cancellation.

Another extremely important advantage of inertial tracking which is successfully demonstrated by the prototype is speed. The lag is certainly no greater than 1 ms, as an update rate of 1 kHz is possible with the graphics disabled. According to an analysis of the phase response, the effective lag is only 0.1 ms. The bandwidth is also more than adequate for human motion-tracking applications.

The noise and resolution results are also encouraging. Because the inertial tracker integrates the sensor data, the resolution of the outputs is much finer than the resolution of the A/D converters used to sample the sensor data. Even with 11-bit effective conversion precision, the high frequency noise in the outputs is only 0.008° RMS or 0.05° peak-to-peak. By comparison, the orientation jitter shown in [Liang *et al.*, 1991] for a Polhemus Isotrak is on the order of 0.3° peak-to-peak.

Although the yaw drift rates of about 100–300°/hr achieved by this prototype are tolerable for opaque VE applications with no interaction with the real environment, the drift accumulated after several minutes would be enough to make contact with the real environment confusing. Once the magnetic compass system for yaw drift compensation is implemented, applications requiring registration of the real and virtual worlds will also be possible. However, it is still desirable to reduce the uncompensated drift rate, because the product of the drift rate and the interval between corrections determines the bound on the system accuracy. As the drift rates intrinsic to the Systron-Donner angular rate sensors are about 30 times smaller than those achieved, it should be easy to make significant reductions by replacing the 12-bit A/D converters with 16-bit ones, adding anti-aliasing filters, and improving the software.

Further work is planned in three principle areas: 1) development of a second prototype orientation tracker, 2) incorporation of the inertial tracker into a complete VE system, and 3) extension to 6 DOFs.

The purpose of developing a second prototype orientation tracker is to progress from the research stage into the production of a practical inertial head-tracker which can be easily incorporated into any standard VE system and used in real applications. The second prototype will incorporate new angular rate sensors in order to achieve a drastic reduction of size and weight. All the electronics will be integrated on a printed circuit card to be housed in an expansion slot of the PC, so that the entire head-tracker system will consist of a PC and a small sensor block with one long thin cable that plugs into the back of the PC. The sensor block will also include a magnetic heading sensor for yaw drift compensation. Finally, the software will be extended to provide rs-232 and perhaps also ethernet interface

capabilities so that head-tracker data may be transferred to a host computer running VE software. This will allow compatibility with existing VE software, and also permit direct performance comparisons to be made between the inertial tracker and its rivals. The testing apparatus will be modified to accommodate a variety of different head-trackers and receive their outputs via rs-232. It will then be possible to test a variety of head-trackers, including the second prototype inertial tracker, using identical methods.

As soon as the new prototype is built and tested, it will be incorporated into a complete VE system and tried out in a VE application. Although the specifications measured in Section 4 tell a great deal about the performance of a head-tracker, much more can still be learned by actually using it for its intended purpose. Subjective evaluation of the inertial head-tracker in operation may uncover additional problems which have not been addressed by the evaluation procedures of Section 4.

The most important and challenging direction for further work is the extension of the inertial head-tracker to track position as well as orientation. Having shown that inertial techniques are well suited for tracking orientation, it is still an open question whether they are useful for tracking position. If it is found that neither accelerometers alone nor accelerometers combined with an ultrasonic aiding system can provide a good solution to the position-tracking problem, this should not be taken to mean that the results obtained for orientation-tracking are useless. Firstly, there are applications which only require orientation tracking, for which the inertial tracker is an ideal solution. Secondly, there are other position tracking methods without range restrictions which may someday be viable. For example, the "self-tracker" proposed by Gary Bishop [Ward *et al.*, 1992] senses self-motion based on optical flow generated by cameras moving through an unstructured visual environment. The "self-tracker" requires computer vision which is currently beyond the state of the art, but if reliable orientation data were available from an inertial subsystem, the computations involved could be simplified tremendously. An excellent solution to the 6 DOF tracking problem will someday be found, and it is the authors' opinion that inertial sensors will be part of it.

Acknowledgments

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